DIVISION S-6—SOIL & WATER MANAGEMENT & CONSERVATION

Effective Rainfall in Poorly Drained Microirrigated Citrus Orchards

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ABSTRACT

Effective rainfall (ER) is the portion of total rainfall that plants use to help meet their consumptive water requirements, and is an important component of water resource budgeting for irrigation. The USDA's Technical Release no. 21 (TR-21) is used to predict ER and irrigation requirements for south Florida citrus, but its accuracy is in question due to high-intensity rainfall, poorly drained soils, and partial irrigation coverage in microirrigated orchards. We evaluated the calculation of ER by TR-21 under these conditions by monitoring rainfall, irrigation, water table depth, evapotranspiration (ET), and soil water content inside and outside of the microirrigation-wetted pattern in four orchards for a total of 83 site-months. We developed a soil water budget to calculate daily water table upflux, root zone water content, water used, and ER separately for the irrigated and nonirrigated root zones. Water budget ER calculated by site ranged between −3.3% and +18.2% of TR-21 ER, with a mean of +10%. A linear correlation between water budget ER and TR-21 ER using pooled data from all four sites yielded the equation: Water Budget ER (mm) = 0.79 [TR-21 ER (mm)] + 17.7, *r* = 0.84. A hypothetical ER comparison using 30-yr mean rainfall and ET data showed that annual ER calculated by TR-21 amounted to 673 mm, while water budget ER totaled 744 mm, or +10.5%. We suggest that the TR-21 method has the level of accuracy needed to allocate water for microirrigated citrus on poorly drained south Florida soils.

THE PORTION of total rainfall that plants use to help meet their consumptive water requirements is termed ER (USDA, 1970). Effective rainfall is often an important component of irrigation requirement estimates. Technical Release no. 21 has been used worldwide to predict irrigation requirements (USDA, 1970). However, developments since 1970 have provided better analytical tools and data for more precise estimates of water requirements (Martin et al., 1993). Additionally, researchers have identified specific problems when using TR-21 under the high-intensity rainfall and poorly drained soil conditions typical of south Florida (Uribe et al., 1995).

A comparison of the USDA-SCS 1967 ER estimation method (later known as the TR-21 method) with a more precise water balance model indicated that this method overpredicted ER for a slowly permeable, poorly drained soil (Patwardhan et al., 1990). Soon after its development, TR-21 was generally recognized to be applicable to areas receiving low intensity rainfall, and to soils that have high infiltration rates (Dastane, 1974). The data used to develop the ER equation in TR-21 were obtained before the development of microirrigation. Since only part of the field surface area is wetted with microirrigation, this could seriously affect estimates of the irrigation requirement for microirrigated crops. Most Florida citrus is microirrigated with drip or microsprinkler irrigation systems. The USDA-NRCS has cautioned users regarding the limitations of TR-21 (USDA, 1993).

Although annual rainfall for peninsular Florida usually exceeds 1300 mm, the majority occurs in summer. Additionally, the soils on which most citrus is grown in south Florida are sandy with low water-holding capacity. The uneven rainfall distribution and sandy soils are the primary factors that necessitate irrigation for commercial Florida citrus production. Most south Florida soils are poorly drained in an undisturbed state. Since citrus roots are sensitive to excess water (Calvert et al., 1967), water management must include drainage as well as irrigation. Drainage is typically a combination of bedding (0.5- to 1-m high double-row beds) and collector ditches from which water is removed either by pumping or gravity flow.

The flux of water supplied by upward capillary movement from a deep water table is small or nonexistent, so it is not taken into account in the TR-21 procedure. However, a water table is often present close enough to the tree root zone in poorly drained soils to significantly augment soil water available for root uptake, reducing the irrigation requirement (Obreza and Admire, 1985). In addition, the presence of a water table limits the penetration of citrus roots to ≈0.45 m (Calvert et al., 1967), which reduces the potential for ER.

The relationship between irrigation requirement (IR) and the other components of the water budget is:

$$IR = ET_C + \Delta\theta - UF - ER, \quad [1]$$

where ET_C is citrus evapotranspiration, $\Delta\theta$ is change in root zone soil water stored, and UF is upward flux from the water table. All water budget components have the same units, volume per unit area, expressed as depth.

The value of ET_C can be estimated from daily refer-

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Abbreviations: DP, deep percolation; ER, effective rainfall; ET, evapotranspiration; IR, irrigation requirement; SF, soil water storage factor; TR-21, SWFREC, Southwest Florida Research and Education Center; USDA Technical Release no. 21.

ence ET (ET_O), a crop coefficient (K_C), and a soil water availability factor (K_S):

$$ET_C = ET_O \times K_C \times K_S. \quad [2]$$

ET_O can be computed from the Penman equation (Jones et al., 1984) or the modified Blaney-Criddle equation (Allen et al., 1999; Shih et al., 1977), or it can be estimated from pan evaporation (Smajstrla et al., 1989). Crop coefficients can be determined by the approach suggested by Snyder et al. (1987), or obtained specifically for humid-region citrus trees from Rogers et al. (1983). The effect of K_S on ET rate can be described using linear or nonlinear functions (Jensen et al., 1971; Hanks, 1974).

On a monthly basis, $\Delta\theta$ for sandy soils is small and can typically be ignored. On a daily basis, however, $\Delta\theta$ is important and is the central component within the water-budgeting procedure that triggers an irrigation. Upward flux from a shallow water table can be determined from the soil water characteristic curve and the saturated hydraulic conductivity (Skaggs, 1980).

Effective rainfall is computed as:

$$ER = P - RO - DP \quad [3]$$

where P is precipitation, RO is run-off, and DP is deep percolation (precipitation that moves below the root zone).

Run-off and DP are difficult to measure accurately in the field. However, if we assume that the surface water volume that runs off a large relatively flat field equals the volume that runs on, and if we assume that ER cannot exceed the daily soil water deficit (the difference between field capacity and soil water content for the day) then ER can be computed directly from Eq. 1.

USDA-NRCS analyzed 50 yr of rainfall records at 22 locations throughout the USA to develop an empirical equation for ER, which is given in TR-21 (USDA, 1970) as:

$$ER = SF \times (0.70917 \times P_m^{0.82416} - 0.11556) \times 10^{0.02426 ETc} \quad [4]$$

where SF is the soil water storage factor, and P_m is the average monthly precipitation (inches).

Converted to SI units (precipitation and ET_C entered as mm), Eq. [4] becomes:

$$ER = SF \times [0.70917 \times (P_m/25.4)^{0.82416} - 0.11556] \times 10^{0.000955 ETc} \quad [5]$$

The SF is given in TR-21 as:

$$SF = 0.531747 + 0.295164 \times D - 0.057697 \times D^2 + 0.003804 \times D^3 \quad [6]$$

where D represents the usable soil water storage (inches). Converted to SI units (D entered as mm), Eq. [6] becomes:

$$SF = 0.531747 + 0.295164\ (D/25.4) - 0.057697\ (D/25.4)^2 + 0.003804\ (D/25.4)^3 \quad [7]$$

In this research, the term D was taken as 0.66 times the available soil water-holding capacity of the crop root zone (Smajstrla et al., 1989).

Another difference in the ER computation for high water table soils is found when considering the DP term. In a soil without a water table, rainfall that is not held in the root zone by capillarity will drain freely. This water, referred to as DP, is lost to the plant and does not become part of ER. The soil water distribution in a freely-draining profile following wetting by rain depends on the soil pore size distribution plus lateral and vertical boundary conditions. After some time following rainfall, drainage becomes imperceptible, and the soil water content is said to be at field capacity. In a freely-draining sandy soil, field capacity may be attained within 1 or 2 d following rainfall (Hillel, 1980). Effective rainfall would be that portion of rain that is stored in the root zone following attainment of field capacity.

The water in a soil with a shallow water table can be divided into two zones: the ‘‘saturated’’ zone below the water table, and the unsaturated zone above it. The soil water distribution under these conditions does not represent a freely drained condition, but drains to equilibrium with capillary rise from the water table. A portion of the rainfall that infiltrates into such soil conditions will be delayed from draining away from the root zone for several days, and may cause the water table to rise (Skaggs, 1980). If the downward movement of rainfall is slowed due to a water table, its residence time in the plant root zone will increase, possibly affecting the amount of ER.

Florida's water-regulating agencies require accurate estimates of the components of the citrus water budget in order to fairly allocate irrigation water resources to citrus growers. Since ER is an important component of a water budget under humid conditions, the objective of this work was to evaluate the current method of estimating ER (TR-21) for Florida citrus on poorly drained soils.

Table 1. Characteristics of four citrus orchards in which water budget measurements were conducted.

	Soil series			
Characteristic	**Immokalee**	**Basinger**	**Boca**	**Malabar**
Time period for data collection	**Oct. 1995–Oct. 1997**	**Oct. 1995–Sep. 1997**	**Apr. 1996–Sep. 1997**	**June 1996–Sep. 1997**
Landscape position	**Flatwoods**	**Slough**	**Flatwoods**	**Slough**
Soil textural class	**Fine sand**	**Fine sand**	**Sand**	**Sand**
Orchard block size, ha	**6.5**	**3.3**	**5.7**	**8.1**
Tree spacing, m	**4.6**	**3.7**	**5.5**	**4.0**
Row spacing, m	**6.7**	**7.3**	**7.9**	**7.0**
Emitter flow rate, L hr^{-1}	**91**	**53**	**28**	**39**
Rooting area per tree, m^2	**22.4**	**19.5**	**31.8**	**20.3**
Soil water-holding capacity, m m^{-1}	**0.092**	**0.117**	**0.171**	**0.083**

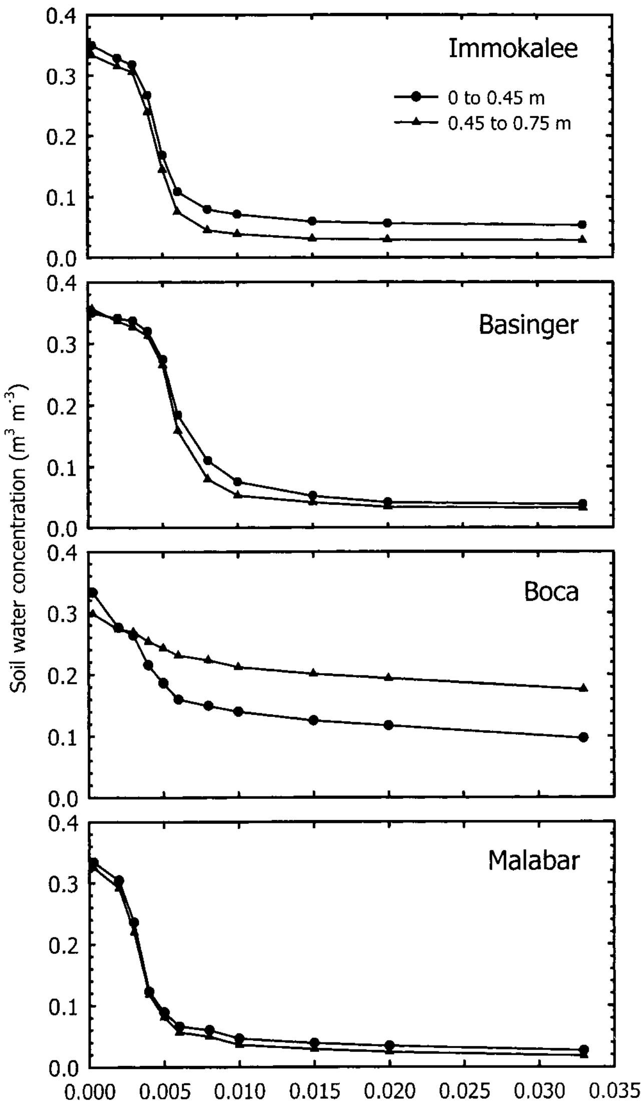

Fig. 1. Soil water characteristic desorption curves within (0 to 0.45 m) and below (0.45 to 0.75 m) the root zone at each site.

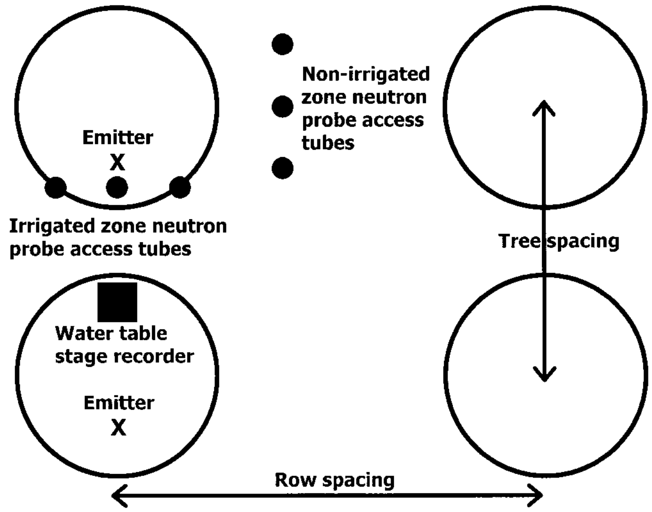

Fig. 2. Diagram of field data acquisition sites. Individual citrus trees are represented by the large circles.

MATERIALS AND METHODS

Citrus Orchard Sites

Four citrus grower-cooperators provided orchard sites for monitoring rainfall volume and temporal distribution, irrigation water application volumes, root zone soil water content, and water table fluctuations (Table 1). The orchards are referred to by the name of the soil series found there [Immokalee (sandy, siliceous, hyperthermic Arenic Alaquods), Basinger (siliceous, hyperthermic Spodic Psammaquents), Boca (loamy, siliceous, superactive, hyperthermic Arenic Endoaqualfs), and Malabar (loamy, siliceous, active, hyperthermic Grossarenic Endoaqualfs)]. Immokalee and Basinger were located in Collier County, while Boca and Malabar were located in Hendry County, FL. The Immokalee site was owned by the state of Florida and was located at the University of Florida, Southwest Florida Research and Education Center (SWFREC). The other three sites were commercial orchards. Each orchard consisted of 7- to 10-yr-old, healthy, solid-set orange (*Citrus sinensis* L.) trees with few skips or young replants, a microsprinkler irrigation system with one sprinkler per tree that wetted a 7.2-m^2 area under the canopy, and typical two-row bed configuration and surface drainage.

Soil Characteristics

The soil profiles observed at each site were typical of Florida citrus orchards on poorly drained soils. Soil core samples taken in irrigated and nonirrigated areas under the trees indicated that almost all citrus roots were confined to the top 0.45 m of soil. We determined root density in the cores by removing the roots, laying them on a grid, and counting root-grid line intersections as described by Tennant (1975). Root density in the 0- to 0.15-, 0.15- to 0.30-, and 0.30- to 0.45-m depth increments averaged 0.85, 0.32, and 0.07 cm roots cm^{-3} soil, respectively. Root density was the same within the irrigated and non-irrigated zones, which was not a surprising observation considering that rainfall keeps the nonirrigated rooting volume wet for most of the year, allowing roots to proliferate throughout. Therefore, we assumed a laterally-uniform, 0.45-m deep root zone for all sites in the water-budgeting procedure.

The soil series at each site was identified by hand-excavating and observing the soil profile (H. Yamataki, 1995, USDA-NRCS, personal communication). Observations revealed that the root zone soil textural class was either sand or fine sand, with single-grain or weak fine granular structure. The top of the spodic horizon in the Immokalee soil was ≈1.3 m below the bed surface. The top of the argillic horizons in the Boca and Malabar soils were ≈0.65 and 1.3 m below the bed surface, respectively. The Basinger soil did not have a water-flow restrictive layer in the profile. Root zone soil water characteristic desorption curves, measured with a pressure plate apparatus (Klute, 1986) indicated large soil pore sizes and a narrow pore-size distribution in all orchards except Boca (Fig. 1). We obtained the soil water-holding capacities used in the water-budgeting procedure from these curves using soil water tensions of 0.008 MPa as field capacity and 1.5 MPa as wilting point.

Because the orchards were constructed using a two-row bed design, each alternate row middle was a gently-sloping water furrow (v-ditch) with bottom ≈0.9 m below the top of the bed. Citrus roots were inhibited from growing towards the water furrow due to its downward slope, so the potential rooting area for each tree was less than if the orchard was planted without beds for drainage. We estimated that the root-

Table 2. Citrus microirrigated water budget inputs and outputs to calculate ER. Outputs were calculated on a daily basis, separately for the irrigated and nonirrigated root zones.

Abbreviation	Definition	Units	Origin or derivation
		Inputs	
WETAREA	Ground surface area wetted by one microsprinkler.	m^2	Measured in the field.
TREEAREA	Ground surface area under which the roots of one tree exist.	m^2	Measured in the field.
ROOTDEP	Citrus tree rooting depth.	m	Measured in the field.
WHC	Soil water-holding capacity.	$m\ m^{-1}$	Measured in the laboratory using nondisturbed soil cores.
IRRTIME	Irrigation system run time per day.	hr	Measured in the field.
EMITFLOW	Microsprinkler flow rate.	$L\ hr^{-1}$	Measured in the field.
APPEFF	Water application efficiency for microirrigation system.	decimal	Assumed to be 0.90 for microsprinkler irrigation.
RAIN	Daily rainfall.	mm	Measured in the field.
WTD	Water table depth.	m	Measured in the field.
ET_O	Reference evapotranspiration.	mm	Estimated from Penman equation (Jones et al., 1984).
K_C	Crop coefficient.	decimal	Obtained from Rogers et al. (1983).
K_S	Soil water stress coefficient.	decimal	If $\%\theta_{PREV} \geq 50$, then $K_S = 1$. If $\%\theta_{PREV} \leq 33$, then $K_S = 0$. If $33 < \%_{PREV} > 50$, then $K_S = (\%_{PREV} \times 0.0625) - 2.125$.
ET_C	Citrus evapotranspiration.	mm	$ET_C = ET_O \times K_C \times K_S$.
STORCAP	Soil water storage capacity.	$L\ tree^{-1}$	For the irrigated root zone: STORCAP = WETAREA × ROOTDEP × WHC × 1000 $L\ m^{-3}$. For the nonirrigated root zone: STORCAP = (TREEAREA × ROOTDEP × WHC × 1000 $L\ m^{-3}$) − irrigated zone STORCAP.
UPFLUX	Upward flux from the water table.	mm	Estimated using the SOILPREP procedure in DRAINMOD (Skaggs, 1980) (Fig. 3).
θ_{MAX}	Maximum root zone soil water content.	mm	WHC × ROOTDEP × 1000 $mm\ m^{-1}$.
θ_{ADDED}	Water added to the root zone.	$L\ tree^{-1}$	For the irrigated zone: θ_{ADDED} = (IRRTIME × EMITFLOW × APPEFF) + (RAIN × WETAREA) + (UPFLUX × WETAREA). For the nonirrigated zone: θ_{ADDED} = RAIN × (TREEAREA − WETAREA) + UPFLUX × (TREEAREA − WETAREA).
		Outputs	
θ_{STORED}	Water stored in the root zone.	$L\ tree^{-1}$	If θ_{ADDED} + (STORCAP × $\%\theta_{PREV}$)/100 − θ_{USED} < STORCAP/3, then θ_{STORED} = STORCAP/3. Else if θ_{ADDED} + (STORCAP × $\%\theta_{PREV}$)/100) − θ_{USED} > STORCAP, then θ_{STORED} = STORCAP. Else θ_{STORED} = θ_{ADDED} + (STORCAP × $\%\theta_{PREV}$)/100) − θ_{USED}.
$\%\theta$	Water stored in the root zone as a percentage of STORCAP.	%	$\%\theta$ = (θ_{STORED}/STORCAP) × 100†.
θ	Volume of water stored per unit area.	mm	θ = ($\%\theta$/100) × WHC × ROOTDEP‡.
θ_{USED}	Water used by the citrus trees.	$L\ tree^{-1}$	For the irrigated zone: $\theta_{USED} = ET_C$ × WETAREA. For the nonirrigated zone: $\theta_{USED} = ET_C$ × (TREEAREA − WETAREA).
θ_{LEACH}	Water leached from the root zone.	$L\ tree^{-1}$	If θ_{ADDED} + (STORCAP × $\%\theta_{PREV}$)/100) − θ_{USED} > STORCAP, then $\theta_{LEACH} = \theta_{ADDED}$ + (STORCAP × $\%\theta_{PREV}$)/100) − θ_{USED} − STORCAP. Else θ_{LEACH} = 0.
ER	Effective rainfall	mm	If RAIN ≤ ($\theta_{MAX} - \theta_{PREV} + ET_C$), then ER = RAIN. Else ER = ($\theta_{MAX} - \theta_{PREV} + ET_C$).

† % θ for the previous day is noted as $\%\theta_{PREV}$.
‡ θ for the previous day is noted as θ_{PREV}.

ing area per tree was 73% of the area allotted to each tree by the row and tree spacing. The remaining 27% was water furrow, where no roots grew.

Instrumentation

Monitoring equipment installed at a single site in the interior of each orchard included a recording rain gauge, a continuous water table stage recorder, an accumulating water meter attached to the irrigation submain, and two nests of three neutron probe access tubes, one each in the irrigated and nonirrigated root zones (Fig. 2). We measured soil water content to a depth of 0.75 m in 0.15-m increments weekly at each site throughout the study period using a neutron soil moisture meter (Model 503DR, Campbell Pacific Nuclear Corp., Martinez, CA).

We calibrated the neutron meter by installing temporary neutron probe access tubes in the irrigated and nonirrigated root zones at all sites. Count/standard count ratios were measured in 0.15-m depth increments from the surface. Immediately afterward, we removed the tubes and took six soil samples with a volumetric core sampler at each depth increment in a circular pattern adjacent to the holes left by the tubes. We plotted the mean volumetric water content for each depth against the count ratios to define the calibration relationship, and developed two linear calibration equations for each site: one for the top 0.15-m depth and one for the 0.30- to 0.75-m depths. The simple linear correlation coefficients for these equations ranged between 0.85 and 0.99.

Water Budget Calculation

We calculated a water balance using a customized computer spreadsheet to budget the daily water at each citrus orchard site. The irrigated and nonirrigated citrus root zones were calculated separately. Inputs to the budget included site-specific soil and irrigation system characteristics (Table 1), as well as daily measurements or estimates of water table depth, rainfall, upward flux from the water table (Fig. 3), irrigation system run time, ET_O, K_C, K_S, and other parameters (Table 2). We used the Penman equation (Jones et al., 1984) to estimate ET_O with climatological data obtained from the SWFREC weather station, which was located 0.2 km east, 3 km west, 16 km south, and 32 km south of the Immokalee, Basinger, Boca, and Malabar sites, respectively. Monthly K_C values were obtained from Rogers et al. (1983).

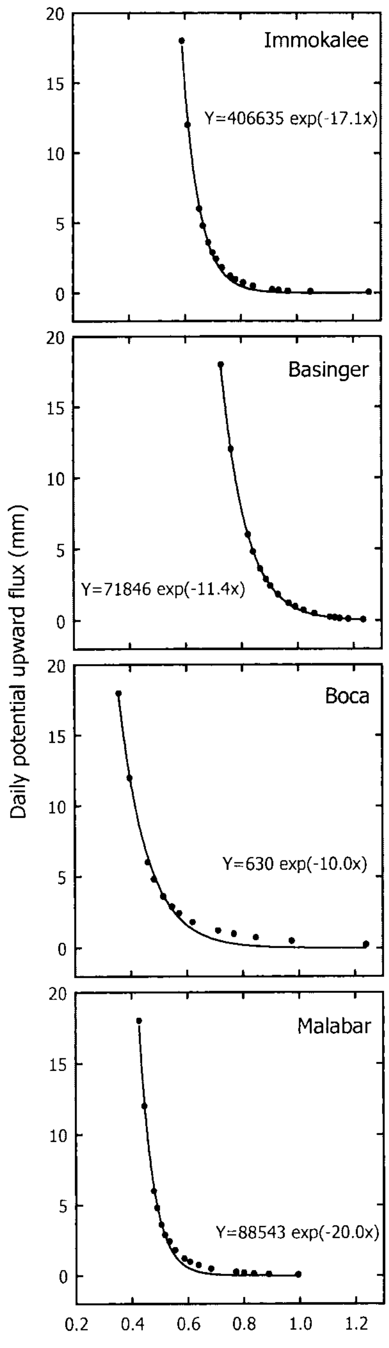

Fig. 3. Upward flux-water table depth relationships for the soils at the four field sites.

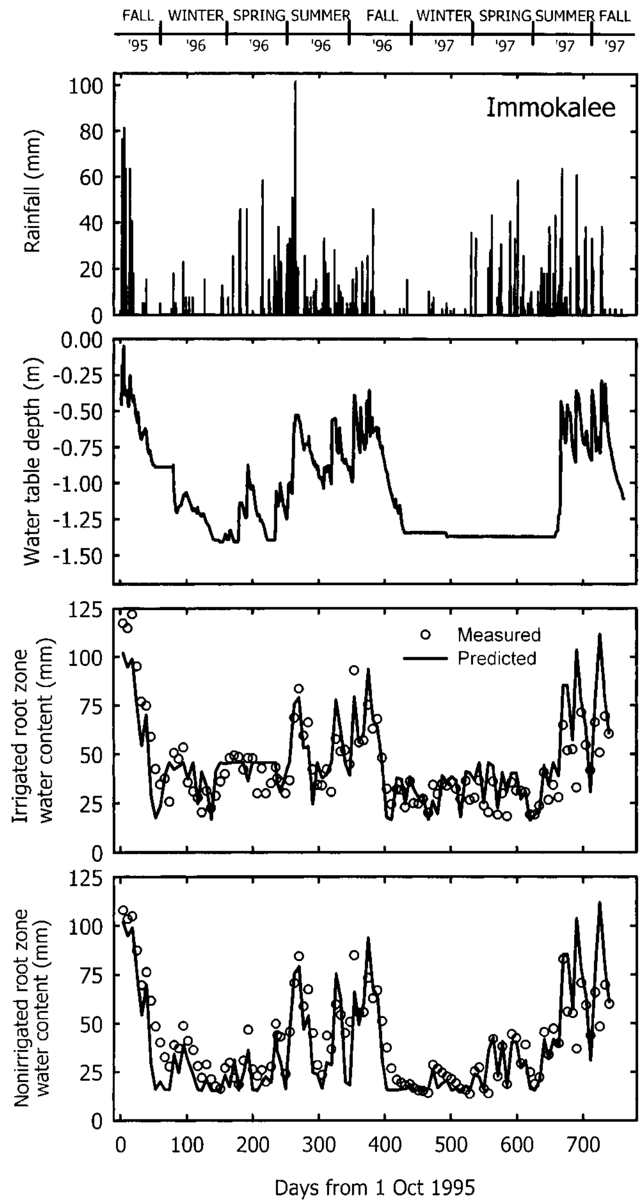

Fig. 4. Rainfall, water table depths, and measured and predicted soil water contents for the irrigated and nonirrigated root zones with time at the Immokalee site.

Most water extraction models assume that soil water is available to plants until the wilting point is reached (Allen et al., 1999). However, it has been our experience that in coarse-textured soils, citrus extracts little or no water when the soil contains less than 33% of available water. Therefore, we arrived at values for K_S in the following manner: Field observations indicated that citrus trees could extract all or nearly all of the water demanded by the atmosphere when soil water stored in the root zone (%θ) was between 100 and 50% of θ_{MAX} (the difference between field capacity and wilting point). Therefore, we set K_S equal to 1 for %θ in the range of 50 to 100% of θ_{MAX}. When %θ was below 33% of θ_{MAX}, no water uptake was assumed ($K_S = 0$). We assumed that as %θ decreased from 50% to 33% of θ_{MAX}, K_S decreased linearly from 1 to 0 (Table 2). The water balance calculation checked the daily value of %θ in the irrigated and nonirrigated root zones and assigned the appropriate value for K_S for the daily ET_C calculations for each zone.

Water budget outputs, which we calculated separately for the irrigated and nonirrigated root zones each day, included water stored in the root zone (θ_{STORED}), water used by the citrus trees (θ_{USED}), water leached from the root zone ($\theta_{LEACHED}$), and ER (Table 2). We summed daily ER values to produce monthly ER, which was not allowed to exceed monthly ET_C.

Water Budget Validation

We assessed the suitability of the water budget for its intended purpose, evaluation of the TR-21 ER estimation for

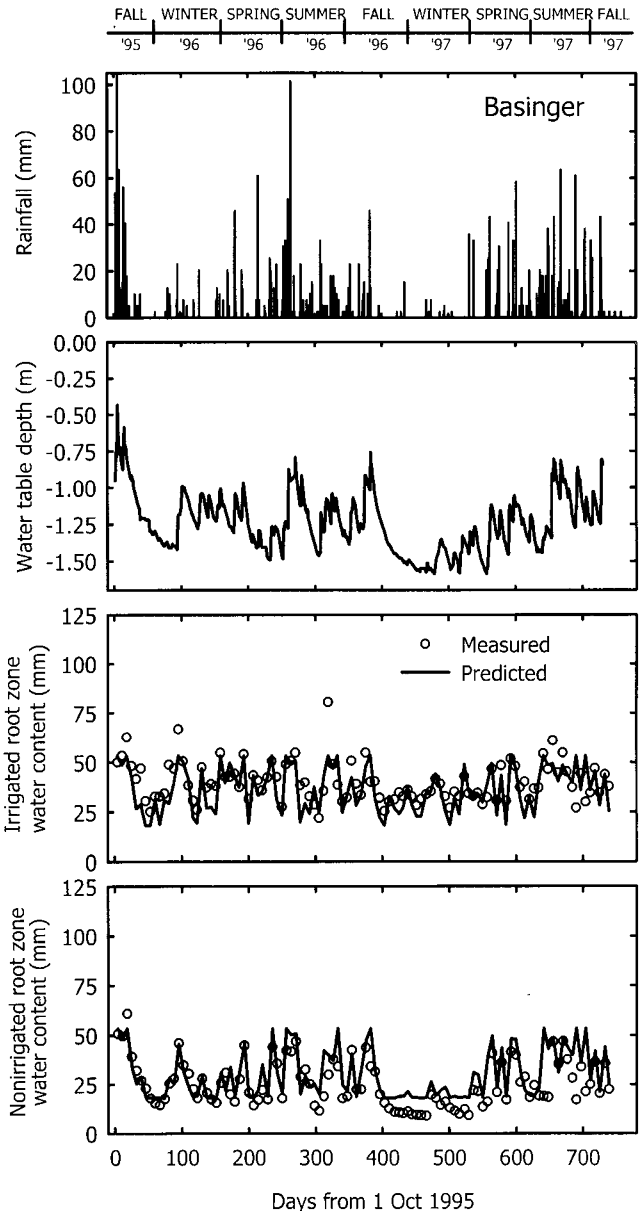

Fig. 5. Rainfall, water table depths, and measured and predicted soil water contents for the irrigated and nonirrigated root zones with time at the Basinger site.

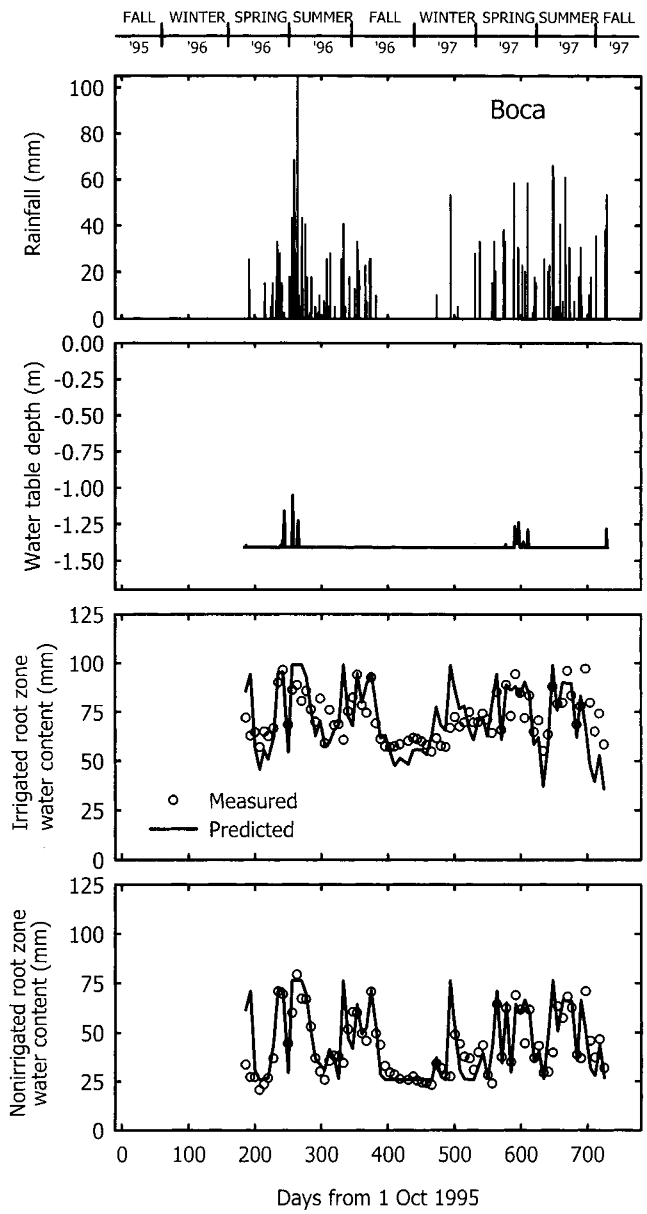

Fig. 6. Rainfall, water table depths, and measured and predicted soil water contents for the irrigated and nonirrigated root zones with time at the Boca site.

humid-region citrus on sandy, high water table soil, by comparing predicted with measured soil water content. We plotted predicted root zone water content against measured water content for the days when neutron moisture measurements were made, calculated a simple linear correlation, and tested the significance of *r*. To gauge the suitability of TR-21 for calculating ER for Florida citrus on poorly drained soils, we calculated monthly TR-21 ER and plotted the resulting values against ER calculated by the water budget by site. In the TR-21 calculation, monthly ER was not allowed to exceed monthly ET_C (USDA, 1970). We calculated the simple linear correlations, and tested the significance of *r*. Finally, we pooled the ER data to determine a regional relationship between ER calculated by the two methods, and made a hypothetical comparison of TR-21 ER and water budget ER for a citrus orchard on a poorly drained soil.

RESULTS AND DISCUSSION

Rainfall and Irrigation Volume and Distribution

Compared with the mean rainfall measured at the SWFREC during the previous 30 yr, rainfall was greater at Immokalee and Basinger, similar at Boca, and less at Malabar during the 2-yr study period (Table 3). Rainfall distribution was typical for south Florida, with high volume and frequency in late spring and summer, and dry periods in the autumn and winter (Fig. 4–7). Irrigation volume was much greater at the Immokalee site compared with the other three sites (Table 3). The primary reason was that the Immokalee orchard was fertilized by adding solution fertilizer to the irrigation water (fertigation), which necessitated extra water applications be-

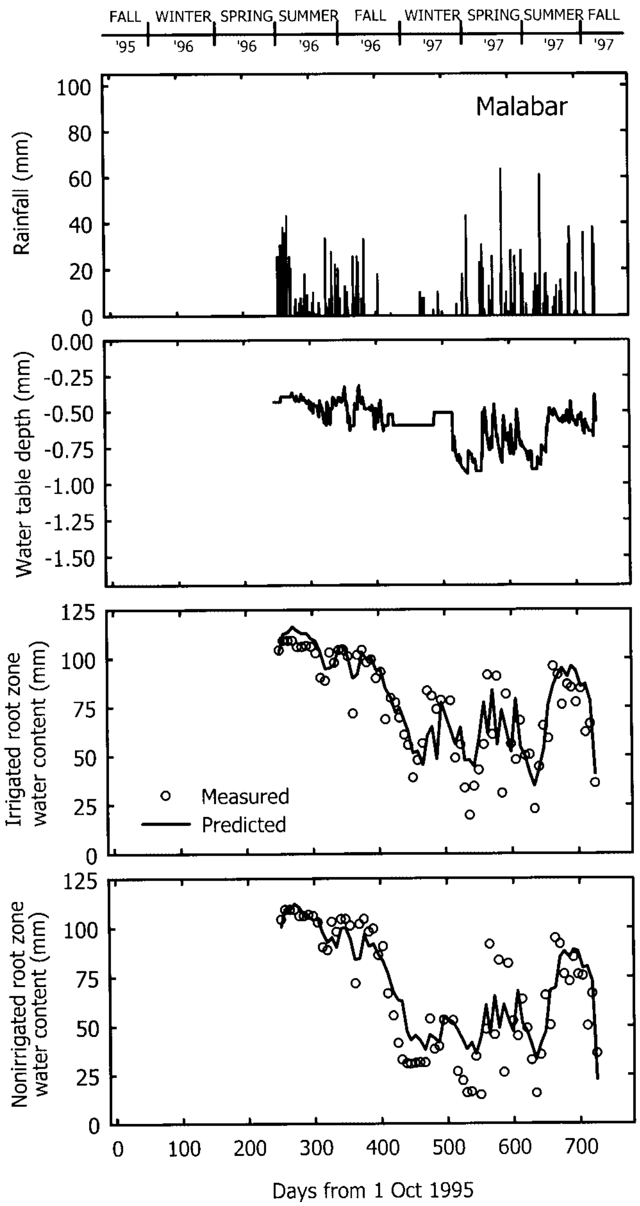

Fig. 7. Rainfall, water table depths, and measured and predicted soil water contents for the irrigated and nonirrigated root zones with time at the Malabar site.

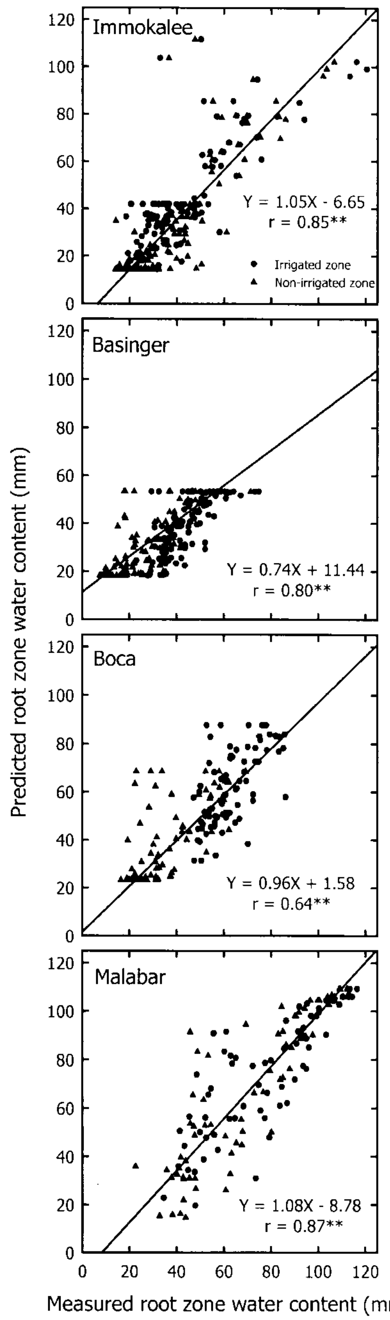

Fig. 8. Correlation between measured and predicted soil water contents for the irrigated and nonirrigated root zones (top 0.45 m of soil).

yond the irrigation requirement. The other three orchards were fertilized by spreading dry fertilizer on the soil surface. Another reason for the irrigation volume difference could have been under-irrigation of the three commercial orchards.

Water Table Fluctuation and Upward Flux

Water table depths and fluctuations at the Immokalee, Basinger, and Boca sites were typical for citrus grown on poorly drained soils, while the Malabar site tended to have a shallower water table due to its lower landscape position in a slough (Fig. 4–7). Upward flux was not detected at the Boca site and relatively small at the Basinger site because the water table was usually too deep (Table 3). Upward flux contributions to citrus water use were important only when the water table was <1 m from the soil surface, which occurred during the summer months at the Immokalee site and during almost the entire study period at the Malabar site.

Water Balance Budget Performance

The performance of the water balance budget at each site, demonstrated by comparing predicted with measured root zone soil water content (θ in the top 0.45 m) for the irrigated and nonirrigated zones, is illustrated in Fig. 4 through 7. Measured and predicted values usually were similar. There was evidence of higher soil water content in the irrigated zone compared with the nonirri-

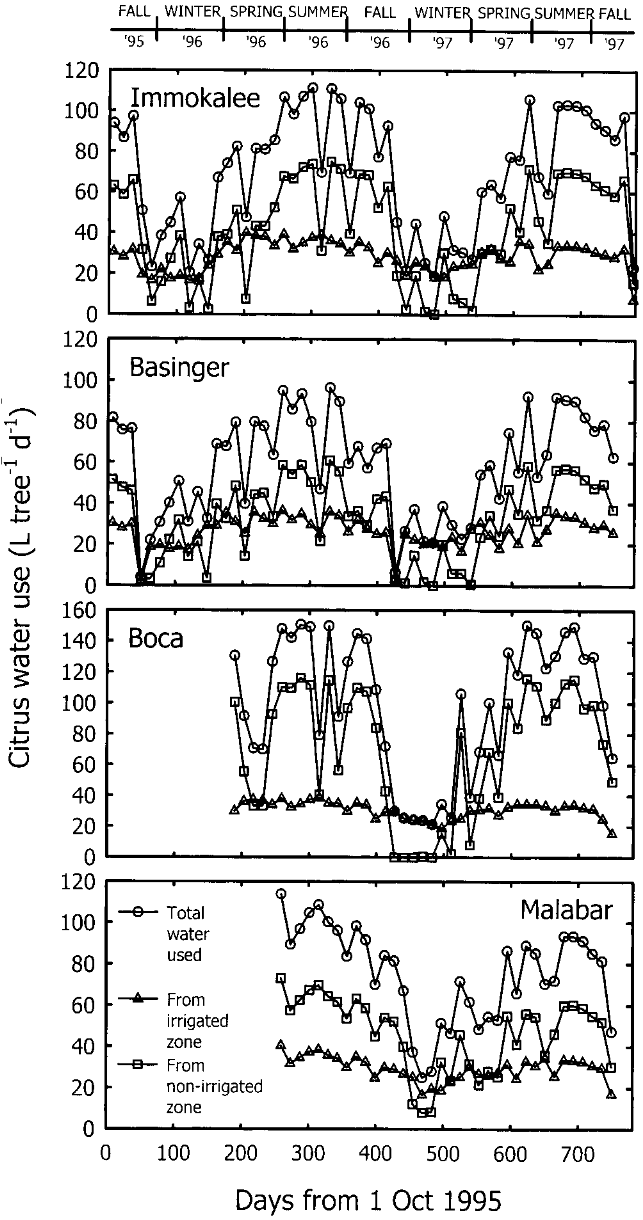

Fig. 9. Citrus water use from the irrigated and nonirrigated root zones with time by site.

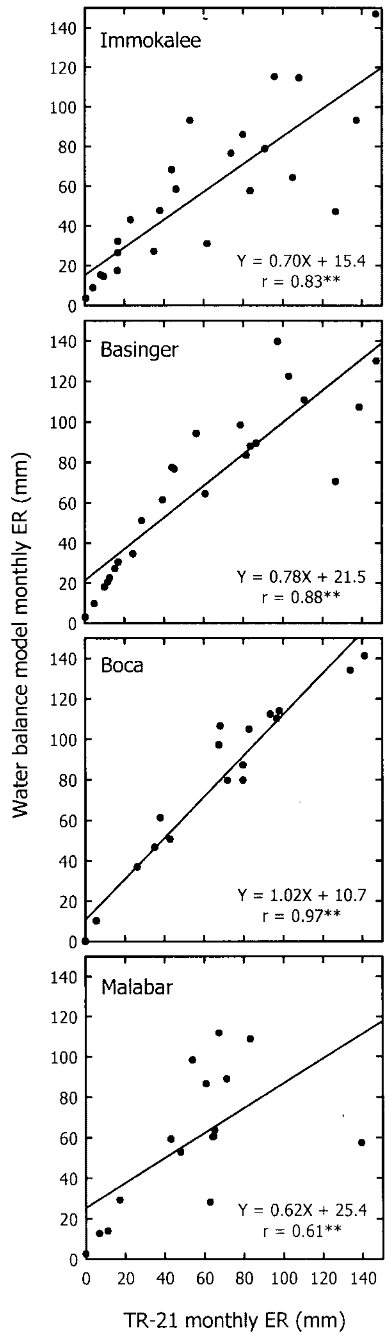

Fig. 10. Correlation between monthly water budget effective rainfall (ER) and TR-21 ER for each site.

gated zone at each site, particularly at Boca, where no upward flux occurred.

Predicted and measured soil water content values were significantly correlated (Fig. 8). A linear regression slope of 1 would indicate that the water budget was accurate. Regression equation slopes ranged between 0.74 and 1.08 among sites. When site data were pooled, regression slopes were 0.99 and 1.07 for the irrigated and nonirrigated root zones, respectively. Data points were not all tightly grouped around the regression line, but the water budget was not designed to predict daily

Table 3. Rainfall, irrigation, upward flux from the water table, and calculated effective rainfall (ER) for four citrus orchards.

Orchard	Total months of data collection	Rainfall (variation from 30-yr mean)	Irrigation	Upward flux from water table	TR-21 ER	Water budget ER	Water budget ER difference from TR-21 ER
		mm					%
Immokalee	25	3077 (+12%)	1351	696	1430	1383	−3.3
Basinger	24	2927 (+10%)	328	276	1423	1632	−14.7
Boca	18	2273 (−1%)	152	0	1161	1372	+18.2
Malabar	16	1652 (−22%)	277	971	859	935	+8.8

Table 4. Monthly long-term rainfall, historical citrus evapotranspiration (ET), and comparison of effective rainfall (ER) calculated by TR-21 and the water budget.

Month	Long-term mean rainfall†	Mean citrus ET	TR-21-calculated ER	ER based on water budget
	mm			
Jan.	47	58	24	37
Feb.	57	69	30	41
Mar.	73	99	39	49
Apr.	51	117	30	41
May	131	122	69	72
June	226	117	108	103
July	203	124	101	97
Aug.	183	117	91	90
Sep.	178	102	86	86
Oct.	98	94	50	57
Nov.	38	71	21	34
Dec.	45	64	24	37
Total	1330	1154	673	744

† Southwest Florida Research and Education Center, 1960–1990.

soil water content to a high level of accuracy. Effective rainfall was calculated on a monthly basis, so daily variations in predicted water budget outputs would be expected to damp out over a month's time. Therefore, the water budget accuracy was deemed appropriate for the purpose for which it was intended.

Temporal Citrus Water Use

Soil water extraction patterns for the irrigated and nonirrigated zones as calculated by the water budget showed that for most of the year, the majority of water used by citrus was extracted from the nonirrigated zone (Fig. 9). A probable explanation for this occurrence is that although root density was uniform throughout the root zone, irrigation covered only 23 to 37% of it. The only times the citrus trees used more water from the irrigated zone than from the nonirrigated zone were during extended drought periods in the winters of 1996 and 1997. During those periods, the remaining water was probably mostly unavailable to the citrus trees because the water content of the nonirrigated zone fell below one-third of the total available soil water.

Effective Rainfall Comparison and Evaluation of TR-21

This research was designed to answer the question of whether or not the TR-21 method for estimating ER gives an accurate picture of ER for microirrigated Florida citrus on poorly drained soils. If we assume that the water budget ER calculations were reasonably accurate, then the most favorable judgement for the TR-21 method would be a 1:1 relationship between monthly TR-21 ER and water budget ER. In a linear correlation analysis, this would be expressed by a slope of 1 and a y-intercept of zero, with a statistically-significant simple correlation coefficient.

The linear correlation between monthly TR-21 ER and water budget ER for each site produced slopes between 0.62 and 1.02, y-intercepts between 10.7 and 25.4 mm, and statistically-significant correlation coefficients (Fig. 10). The fitted lines were not forced through the origin because zero ER determined by one method did not necessarily mean that a zero value would be determined by the other method. As monthly rainfall volume increased, the linear relationship became more diffuse. TR-21 tended to overestimate ER in months where rainfall exceeded 120 mm, especially if there were daily rains in excess of 80 mm within those months. Agreement between TR-21 ER and water budget ER was highest for Boca, followed by Basinger, Immokalee, and Malabar. This order of sites also corresponded to decreasing depth to the water table (Fig. 4–7), hence increasing upward flux (Table 3). As the influence of the water table on root zone soil water content increased, the ability of TR-21 to accurately calculate ER decreased.

When the data from the four sites were pooled to derive a regional relationship for south Florida, the linear correlation equation was:

$$\text{water budget ER} = 0.79\,(\text{TR-21 ER}) + 17.7,\ r = 0.84.$$

We used this equation to make a hypothetical comparison of TR-21 ER and water budget ER for a citrus orchard on a poorly drained soil (Table 4). We calculated TR-21 ER using D for the Immokalee orchard, 30-yr monthly mean rainfall for Immokalee, and the mean monthly citrus ET given by Harrison (1984). TR-21 ER slightly exceeded water budget ER in the three wettest months, and was lower than water budget ER in the drier months. Annual TR-21 ER amounted to 673 mm, while water budget ER determined from the above equation totaled 744 mm. Thus, in this example a citrus orchard on a poorly drained soil would be able to use 10.5% more rainfall than estimated by TR-21.

In the field, water budget ER exceeded TR-21 ER at three of the four sites (Table 3). The lower value of water budget ER compared with TR-21 ER at the Immokalee site was likely due to the large amount of irrigation applied, which did not allow the irrigated zone to store as much rainfall. On average, water budget ER was ≈10% higher than TR-21 ER (Table 3), which is consistent with the above example.

Individuals or agencies that have the greatest interest in the accuracy of the TR-21 method are those involved in long-term water resource allocation because they seek the most efficient allocation of water resources among all users. Since TR-21 is a key component of the water-budgeting process, a judgement needs to be made regarding the 10% difference (71 mm annually) between TR-21 ER and water budget ER found in this study. If the TR-21 method is deemed not sufficiently accurate, then a new method would need to be derived at substantial effort and expense.

Currently in Florida, water supply exceeds demand. Given this situation and considering that the TR-21 ER and water budget ER were within 10% of each other, we suggest that the TR-21 method has the level of accuracy needed for the purpose of water allocation for microirrigated citrus on poorly drained soils in south Florida. However, as Florida's increasing population puts additional demand on available water resources, the method to estimate ER may need refinement to increase its accuracy. A key step in this process would be to incorporate depth to water table as a modification parameter when using TR-21 for citrus on high-water table soils.

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